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New Physics Searches with Isotope Shifts of Two Hg Clock Transitions

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We present the experimental project of searching for physics beyond the Standard Model by looking for breaking of linearity in the King plot of two Hg clock transitions.

Keywords: Hg clock transition, mercury, isotope shift, King plot, fundamental physics

I. Introduction

Hg features a rich isotopic diversity, which, in combination with extremely narrow clock transitions, provides a fascinating perspective of probing new fundamental interactions. We present a practical realization of this idea, which is based on precise measurements of the King plot linearity. This widely used method allows a systematic study of the isotope shifts of two atomic transitions for different isotopes. King-plot based fundamental researches belong to hot topics intensively explored in cold-atomic physics [1-6]. We already used this method for isotope shift spectroscopy and the determination of nuclear parameters of Hg [7]. Hg isotope shift measurements that we have already performed were based on the intercombination $^1S_0$-$^3P_1$ Hg transition. Although our absolute spectroscopic results are the most accurate to date, the relatively large 1.3 MHz linewidth of the transition prevents deeper insight into fundamental aspects of the King plot. A significant improvement of our project explores extremely narrow, clock transitions, $^1S_0$-$^3P_0$ and $^1S_0$-$^3P_2$, with natural linewidths much below 1 Hz [8, 9]. This, together with the high isotopic diversity of Hg, provides excellent conditions to perform state-of-the-art King-plot based measurements and pave the way for experimental verification of the Standard Model.

In addition to the developments in fundamental physics, precise determination of the isotope shift will provide valuable isotope-dependent nuclear parameters of Hg, like mass shift, electronic field shift, and nuclear charge mean-square radii.

To perform fundamental study based on the King plot linearity, an ultra-high accuracy of the isotope shifts measurements has to be assured. For this purpose the clock transitions are particularly suitable. In this project we will perform precise absolute spectroscopy of a double forbidden $^1S_0$ - $^3P_0$ transition in Hg at 266 nm for bosonic and fermionic Hg isotopes. This transition is weakly coupled in fermions (199Hg and 201Hg) due to the mixing of fine structure states $^1P_1$, $^3P_1$ and $^3P_0$. While bosonic isotopes of mercury (196Hg, 198Hg, 200Hg, 202Hg, and 204Hg) have nuclear spin equal to 0, hyperfine interaction can be imitated by addition of small static magnetic field. This leads to the effect of magnetic quenching which enables controlling the linewidth by the magnetic field [10]. The use of ultranarrow transition [11] will significantly improve the accuracy of our previous studies on the King plot in Hg [7].

II. Methods

To provide a narrow spectral linewidth of the clock laser beam for the $^1S_0$-$^3P_0$ transition, a whispering gallery mode fibre laser at 1062 nm will be used as a light source. Its very narrow (below 80 Hz) spectral linewidth will be narrowed down even more with an ultra-stable ULE cavity, enabling spectroscopic measurements at the Hz level accuracy. The frequency of the source laser will be quadrupled with the system made up of a PPLN crystal (single-pass conversion 1062 nm→531 nm) followed by a frequency bow-tie doubling cavity based on BBO nonlinear crystal (531 nm→265.5 nm).

To reduce the light-induced perturbations related to the AC-stark effect, the atoms will be loaded into the optical lattice operating at the magic wavelength (363 nm for Hg) [12]. This ensures that the energy shifts of the ground and excited states are exactly the same which results in no frequency shift due to the lattice trapping light. The lattice beam will be delivered by a set of lasers which consists of a Ti:Sa laser pumped by 18 W of 532 nm light and the frequency doubling bow-tie cavity. The power of the lattice beam will be above 1 W at 363 nm.

A very similar frequency quadrupling system will be used to produce another clock laser beam at 227 nm to probe $^1S_0$-$^3P_2$ transition together with the corresponding magic wavelength at 351.8 nm [13].

Both laser beams will be frequency narrowed with a high-finesse ultra-low expansion cavity designed for 1062 nm and 908 nm wavelengths. The finesse for both wavelengths is expected to be above 100000.

The isotope shift $IS_i^{A'A}$ for *i*-th transition between isotopes with mass numbers A' and A can be expressed as

$IS_i^{A'A} = \frac{A'-A}{A'A} MS_i + E_i \delta \langle r^2 \rangle^{A'A}$, where MS_i stands for the mass shift term, E_i is the electronic field-shift term, and $\delta \langle r^2 \rangle^{A'A}$ is the difference between the nuclear charge mean-square radii of isotopes A' and A. One can normalize the isotope shift by a mass factor $A'A/(A'-A)$, i.e. $\zeta_i^{A'A} = A'A/(A'-A) IS_i^{A'A}$. The linear relationship between normalized isotope shifts in two different transitions i and j allows eliminating $\delta \langle r^2 \rangle^{A'A}$ term leading to a linear King-plot dependence $\zeta_i^{A'A} = a \zeta_j^{A'A} + b$, where the coefficients a and b do not depend on the isotope parameters. If we consider King-plot dependence in the presence of a new hypothetical particle, we notice breaking its linearity due to a new term related to additional interaction energy. If, for instance, a new hypothetical particle would be a boson with mass m_φ and the interaction between the electrons and neutrons that are mediated by such a boson would be Yukawa-type $V_\varphi \sim (A-Z) e^{-m_\varphi r}/r$, then a new term $X_\phi = \left\langle -\sum_k \frac{\alpha e^{(-m_\varphi r_k)}}{r_k} \right\rangle$,where α is the fine-structure constant, and k numerates the electrons in the atom, would appear breaking the linearity of the King plot [1].

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References

[1] V. A. Yerokhin, R. A. Müller, A. Surzhykov, P. Micke, and P. O. Schmidt, Nonlinear isotope-shift effects in Be-like, B-like, and C-like argon, Phys. Rev. A 101, 012502 (2020).

[2] C. Solaro, S. Meyer, K. Fisher, J. C. Berengut, E. Fuchs, and M. Drewsenet, Improved isotope-shift-based bounds on bosons beyond the Standard Model through measurements of the 2D3/2 - 2D5/2 interval in Ca+, Phys. Rev. Lett. 125, 123003 (2020).

[3] H. Miyake, N. C. Pisenti, P. K. Elgee, A. Sitaram, and G. K. Campbell, Phys. Rev. Research 1, 033113 (2019).

[4] I. Counts, J. Hur, D. P. L. Aude Craik, H. Jeon, C. Leung, J. C. Berengut, A. Geddes, A. Kawasaki, W. Jhe, and V. Vuletić, Phys. Rev. Lett. 125, 123002 (2020).

[5] J. C. Berengut, C. Delaunay, A. Geddes, and Y. Soreq, Generalized King linearity and new physics searches with isotope shifts, Phys. Rev. Research 2, 043444 (2020).

[6] V. A. Dzuba, V. V. Flambaum, and S. Schiller, Testing physics beyond the standard model through additional clock transitions in neutral ytterbium, Phys. Rev. A 98, 022501 (2018).

[7] M. Witkowski, G. Kowzan, R. Munoz-Rodriguez, R. Ciuryło, P. S. Żuchowski, P. Masłowski, and M. Zawada, Absolute frequency and isotope shift measurements of mercury 1S0 − 3P1 transition, Opt. Express, 27 11069 (2019).

[8] H. Hachisu, K. Miyagishi, S. G. Porsev, A. Derevianko, V. D. Ovsiannikov, V. G. Pal’chikov, M. Takamoto, and H. Katori, Trapping of Neutral Mercury Atoms and Prospects for Optical Lattice Clocks, Phys. Rev. Lett. 100, 053001 (2008).

[9] A. D. Ludlow, M. M. Boyd, J. Ye, E. Peik, P. O. Schmidt, “Optical atomic clocks”, Rev. Mod. Phys. 87, 637-701 (2015).

[10] A. V. Taichenachev, V. I. Yudin, C. W. Oates, C. W. Hoyt, Z. W. Barber, and L. Hollberg “Magnetic Field-Induced Spectroscopy of Forbidden Optical Transitions with Application to Lattice-Based Optical Atomic Clocks”, Phys. Rev. Lett. 96, 083001 (2006).

[11] H. Miyake, N. C. Pisenti , P. K. Elgee , A. Sitaram, G. K. Campbell, “Isotope-shift spectroscopy of the 1S0 → 3P1 and 1S0 → 3P0 transitions in strontium” Phys. Rev. Res. 1, 033113-8 (2019).

[12] H. Katori, M. Takamoto, V. G. Pal’chikov, and V. D. Ovsiannikov “Ultrastable Optical Clock with Neutral Atoms in an Engineered Light Shift Trap”, Phys. Rev. Lett. 91 (2003).

[13] A. Gogyan, P. Tecmer, and M. Zawada, "Multi-reference ab initio calculations of Hg spectral data and analysis of magic and zero-magic wavelengths," Opt. Express 29, 8654-8665 (2021).